



LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

New Critical Experiment Design to Investigate Composite Reflection Effect

C. M. Percher, S. K. Kim, D. P. Heinrichs

June 12, 2014

American Nuclear Society Winter Meeting
Anaheim, CA, United States
November 9, 2014 through November 14, 2014

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

New Critical Experiment Design to Investigate Composite Reflection Effect

C. Percher, S. Kim, and D. Heinrichs

Lawrence Livermore National Laboratory: 7000 East Avenue, Livermore, CA, 94550, percher1@llnl.gov

INTRODUCTION

Composite reflection effects, where a combination of two reflectors act in concert to produce more reactive nuclear systems than either single reflector material separately, is a little known anomaly of criticality safety. The Lawrence Livermore National Laboratory's (LLNL's) Nuclear Criticality Safety Division, in support of fissile material operations, calculated surprisingly reactive configurations when a fissile core was surrounded by a thin, moderating reflector backed by a thick metal reflector. These composite reflector configurations were much more reactive than either of the single reflector materials separately. The calculated findings have resulted in a stricter-than-anticipated criticality control set, impacting programmatic work. The aim of this study is to design an experiment using a 4.5 kg alpha plutonium ball and common reflector materials in combination that will drive it critical. This study could have a profound impact on modern criticality safety practice by alerting practitioners to the potential hazard of composite reflection with everyday reflector materials.

PREVIOUS WORK

The *Anomalies of Criticality Safety*¹ contains a short, two page section on "Complex Reflectors," which cautions that combinations of reflectors can be more reactive than the reflectors separately. The report briefly describes two cases of composite reflectors. The first case showed the combined effect of nickel backed by depleted uranium on the critical mass of a uranium hydride core. These experiments were completed by Paxton, and the published account of the work demonstrated that a composite reflector of 1.27 cm thick Ni backed by 20 cm of depleted uranium yielded a smaller critical mass than either reflector separately². The second case reported in the *Anomalies* results from critical experiments at Pacific Northwest National Laboratory (PNNL) that looked at arrays of low enriched UO₂ rods with 2 cm of water reflection backed by 7.6 cm of depleted uranium. This combination of reflectors was shown to be more effective than either a thick water reflector or a depleted uranium reflector backed by water.

A study³ by researchers at the Russian Federal Nuclear Center- Institute of Technical Physics (RFNC-VNIITF)

presented at the International Conference on Nuclear Criticality (ICNC) in 1995 details calculational and experimental investigations of the reflective properties of combined polyethylene (PE) and beryllium. These two reflector materials were chosen due to their superior reflection ability and wide use in the nuclear industry. For reflector thicknesses greater than 4 cm, the study determined that polyethylene backed with beryllium resulted in a 0.7% reactivity increase at the optimal PE thickness of 1-1.5 cm versus a single beryllium reflector.

Based on the results of these studies, the composite reflector effect is believed to be real and experimentally verifiable.

METHODOLOGY

For calculations presented in this report, the Monte Carlo neutron transport code, MCNP5, version 1.51, developed at Los Alamos National Laboratory, was used. Continuous energy ENDF/B-VII.1 cross sections (.80c) were used in all MCNP5 calculations, save for a few minor constituents where ENDF/B-VII cross sections were unavailable.

RESULTS

Berp Ball Description

The BeRP ball, as described in ICSBEP evaluation PU-MET-FAST-038⁴, is an α -phase sphere of cast plutonium with a mass of 4.484 kg and a diameter of 7.5876 cm. Based on these measured values, the density of the sphere is calculated to be 19.6039 g/cm³. Isotopics of the sphere are 93.284 wt% ²³⁹Pu, 5.95 wt% ²⁴⁰Pu, 0.2 wt% ²⁴¹Pu, 0.028 wt% ²⁴²Pu, and 1130 ppm of ²⁴¹Am. A thin stainless steel cladding surrounds the fissile core. The inner and the outer radii of this cladding are 3.827 and 3.857 cm, respectively. There is a small gap between the fissile hemispheres and the stainless steel cladding.

Composite Reflectors with Polyethylene

The BeRP ball model was used to investigate the composite reflection effects of polyethylene and twelve different candidate metals: nickel (Ni), iron (Fe), chromium (Cr), titanium (Ti), manganese (Mn), Zirconium (Zr), Tungsten (W), aluminum (Al), lead (Pb), cobalt (Co), copper (Cu), and depleted uranium (U).

These specific metals were chosen because they are commonly used as structural materials in nuclear applications. For example, many of these metals are components of stainless steel alloys. In the MCNP model, a layer of polyethylene (PE) of variable thickness was located around the BeRP ball and backed by the metal reflector, which was fixed at 30 cm (infinite) thickness. Figure 4.1 shows a 2D representation of the 3D MCNP geometry used for the calculations. The central, purple region is the spherical BeRP ball, surrounded by the variable thickness reflector of high density polyethylene (HDPE), shown in light blue. The gray area is the 30 cm fixed-thickness metallic reflector.

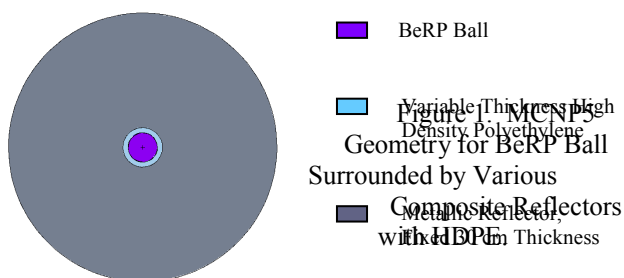


Figure 4.2 displays the results from the MCNP5 calculations for composite reflectors with varying polyethylene thickness backed with 30 cm of various metals. Not all metals displayed the composite effect, namely tungsten and cobalt. The highest reactivity for tungsten (black line, shaded circles) and cobalt (purple line, shaded circles) was calculated when there was no polyethylene reflector at all. Depleted uranium (DU) and polyethylene composite reflectors (red line, shaded circles) displayed interesting behavior as k_{eff} initially decreases with the addition of polyethylene and then displays a composite reflection increase, taking the configuration just above critical around 2 cm of PE thickness. The initial decrease is likely due to the reduced density of the reflector as DU is replaced with PE and increased absorption as neutron energy is reduced through moderation. All other metals displayed some degree of the composite reflection effect, with reactivity increasing with increasing polyethylene reflector thickness and then leveling off and approaching a k_{eff} of 0.9434(2), the reactivity of the BeRP ball reflected by infinite PE alone.

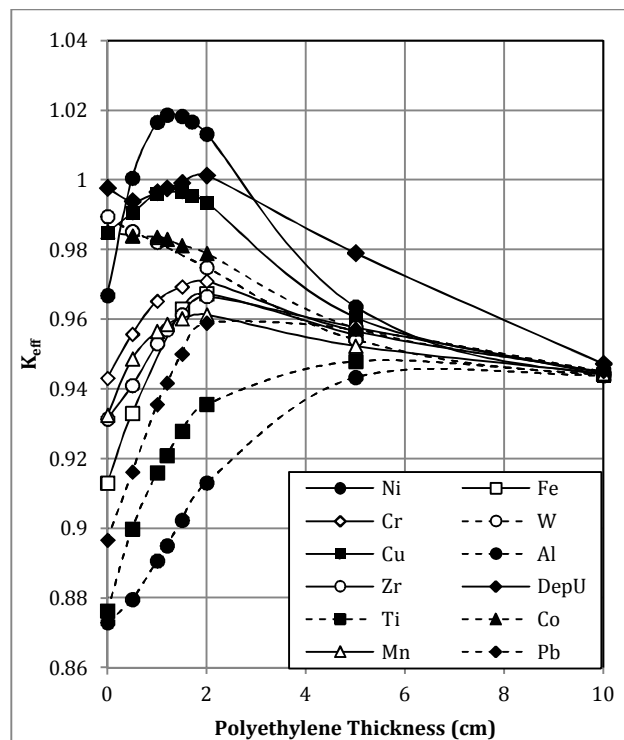


Figure 2. K_{eff} of the BeRP Ball as a Function of Varying Thicknesses of Polyethylene Reflection Backed by 30 cm Thick Metallic Reflectors

From the configurations studied, nickel and PE was shown to have the largest effect on BeRP ball reactivity, peaking at a k_{eff} of 1.0186(2) at 1.2 cm of PE. This corresponds to an increase in k_{eff} of approximately 3.5% from the purely nickel reflected case. The only other reflector combination shown to produce a critical configuration was depleted uranium and polyethylene. However, at a peak k_{eff} of 1.0013(2), this configuration is likely marginal for a critical experiment when experimental realities (such as reflector gaps) are considered. The other combinations of reflector materials failed to produce a critical configuration with the BeRP ball, but could be candidates for critical reflectors for other fissile cores.

Reducing Nickel Reflector Thickness

All preceding calculations were completed using a fixed 30 cm of nickel reflector. Additional MCNP5 calculations were completed that looked at the effect of reducing the nickel reflector. The inner PE thickness was maintained at 1.2 cm and the outer Ni reflector thickness was varied. The results are tabulated in Table 1 and are plotted in Figure 3.

Case ID	Thickness of PE	Thickness of Ni	$k_{\text{eff}} \pm \sigma$
ni0	1.2 cm	0 cm	0.8237 ± 0.0002
ni3	1.2 cm	3 cm	0.9345 ± 0.0002
ni5	1.2 cm	5 cm	0.9629 ± 0.0002
ni10	1.2 cm	10 cm	0.9934 ± 0.0002
ni15	1.2 cm	15 cm	1.0064 ± 0.0002
ni20	1.2 cm	20 cm	1.0128 ± 0.0002
ni25	1.2 cm	25 cm	1.0167 ± 0.0002
ni30	1.2 cm	30 cm	1.0186 ± 0.0002

Table 1: BeRP Ball k_{eff} for PE/Nickel Composite Reflectors for Varying External Ni Reflector Thickness

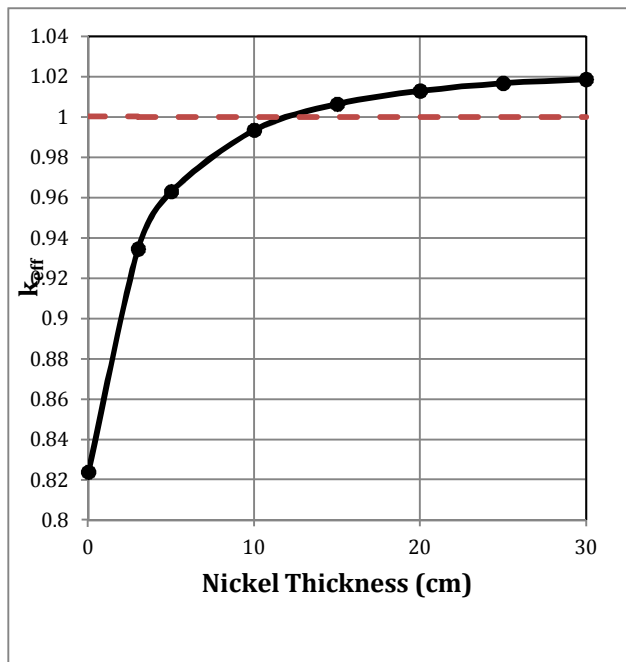


Figure 3: k_{eff} of the BeRP Ball as a Function of Varying Thicknesses of Nickel Outer Reflection with a Fixed 1.2 cm Inner Polyethylene Reflector

With 1.2 cm of PE next to the BeRP ball, the thickness of nickel required to achieve criticality is approximately 12 cm, as shown in Figure 3. With an external nickel thickness of 20 cm, the BeRP composite reflector system has excess reactivity greater than 1%. Therefore, it is likely that the additional 10 cm of reflector, which would be the most costly to fabricate and the most cumbersome to use in the experiment, is unnecessary.

CONCLUSIONS

Polyethylene backed by nickel was calculated by MCNP5 to be the most reactive reflector condition around the BeRP Ball of composite reflectors studied. The optimal

polyethylene thickness was found to be 1.2 cm and the corresponding critical nickel thickness is approximately 12 cm. With a nickel thickness of 20 cm, the excess reactivity of the system, as calculated by MCNP5, is 0.0128.

An investigation of ICSBEP fast critical benchmarks with polyethylene and nickel reflection showed a small positive bias to the MCNP5 calculations. Even when taking this bias into account (0.005 combined Δk), the level of excess reactivity calculated for 1.2 cm of PE and 20 cm of nickel surrounding the BeRP ball provides confidence that a critical assembly can be achieved. A subcritical experiment may also be used to confirm increased multiplication due to composite reflection.

ENDNOTES

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

REFERENCES

1. E.D. CLAYTON, "Anomalies of Criticality Safety, Revision 6." Pacific Northwest National Laboratory. PNNL-19176 (2010).
2. H.C. PAXTON, et al, "Enriched Uranium Hydride Critical Assemblies," *Nuc. Sci. and Eng.*, Vol 7, p 44, (1960).
3. Y.I. CHERNUCHIN, et al, "Composite Polyethylene-Beryllium Neutron Reflector: Anomaly of Criticality Safety," *Proc. of the Fifth Inter. Conf. on Nuc. Crit*, Vol 2, Pages 12/30-33, Albuquerque, NM (1995).
4. J. HUCTIONSON, "Plutonium Sphere Reflected by Beryllium," *Int. Handbook of Evaluated Criticality Safety Benchmark Experiments*, PU-MET-FAST-038, NEA/NSC/DOC (95)03, OECD, (2014).